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INVESTIGATION OF HEAT TRANSFER IN BASE TYPE SUPERSONIC LAMINAR AND TRANSITIONAL SEPARATED FLOWS

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ABSTRACT

Heat transfer rate distributions were measured in the separated regions of a two-dimensional backward facing step, an axially symmetric backward facing step, a blunt two-dimensional base, a sharp protruding two-dimensional leading edge and in the leading edge bubble over the surface of a flat nosed two-dimensional model. All measurements were performed in the straight section of the shock tube at shock Mach numbers between 5.5 to 11, with free stream flow Mach numbers of 1.6 to 2.7, Reynolds numbers (based on the attached flow length or step height) of 3×10^2 to 5×10^5 and stagnation to wall enthalpy ratios of 3 to 50. The results of these measurements are compared with measurements of heat transfer rates in various base type separated flows obtain in various wind tunnels and to a calculation of heat transfer behind a backward facing step based on the integral method. In most of these investigations a high peak in the heat transfer rate is found to occur in the reattachment zone. Maximum heat transfer rate values of up to 10 times the flat plate heat transfer rate are reported in various investigations. An

inverse relation between the value of the peak heat transfer rate and the distance between the separation point to the position of the maximum heating in the reattachment zone is shown to exist.

LIST OF SYMBOLS

a	speed of sound
$B(\kappa_u)$	heat transfer correlation function (Eq. 11)
$C(\kappa_u)$	mixing rate correlation function (Eq. 12)
c_f	friction coefficient
c_q	heat transfer coefficient
$D(\kappa_u)$	skin friction correlation function (Eq. 13)
h	step height (also enthalpy)
H	total enthalpy flux in the x direction in the viscous layer
I	momentum flux in the x direction in the viscous layer
K	mixing coefficient: $(d\delta/dx - \Theta)$
L	length of model ahead of separation
M	Mach number
M_f	free stream flow Mach number over the model in the shock tube
M_s	shock Mach number
$\bar{m}$	mass flux in the x direction in the viscous layer
m	reduced mass flux $m = \bar{m}\, a_{se}$
Nu_x	Local Nusselt number
p	pressure
Pr	Prandtl number
q	local heat transfer rate
$q_{f.p.}$	attached flow heat transfer rate

Re_h	Reynolds number based on h
Re_x	local Reynolds number
Re_L	Reynolds number at the separation position
T	temperature
x	local distance
Δx	distance from separation position
u	velocity in the x direction in the viscous layer
δ	boundary layer or mixing zone thickness
δ_s	boundary layer thickness at separation
δ^*	displacement thickness
δ^{**}	momentum thickness
δ^{***}	energy thickness
Θ	stream line direction relative to the wall at $y = \delta$
κ_h	enthalpy profile shape parameter
κ_u	velocity profile shape parameter
μ	coefficient of dynamic viscosity
ρ	mass density
τ	shear stress
ϕ	auxialiary function

SUBSCRIPTS

e	freestream conditions at $y = \delta$
s	local stagnation conditions
w	conditions at the wall
o	reference conditions
1	mean values of viscous layer

LIST OF FIGURES

I. INTRODUCTION

Flow separation at supersonic and hypersonic speeds is known to have strong effects on the local heat transfer rates to body surfaces particularly in the reattachment zone. In general, it was found that heat transfer rates are decreased in the "dead water" zone and increased in the reattachment zone in comparison with the flat plate heat transfer rates under similar flow conditions. The net increase or decrease of the heat transfer in the separated flow as a whole is not easily determined. In many cases the increase in the heat transfer in the reattachment zone is much greater than the corresponding reduction found in the "dead water" zone In many practical applications, however, the important parameters are the value of the maximum heat transfer rate and the location of his "hot" spot in the reattachment zone.

For the past several years, heat transfer rates in separated flows have been studied in this laboratory. It is the purpose of this paper to summarize some of the more significant results of these studies, to compare the results with other published measurements and to discuss the main parameters affecting the local heat transfer rates in separated flow including also reference to the analytical studies.

The measurements on which this paper is based were made in the supersonic high enthalpy flow in a 3" x 3" shock tube and have included the following model configurations: two-dimensional backward facing step (Ref. 1), axisymmetric

backward facing step (Ref. 2), two-dimensional blunt base (Ref. 3), sharp protruding leading edge (Ref. 4) and two-dimensional leading edge separation bubble (Ref. 5).

The shock tube has been found to be a very useful facility for many types of heat transfer studies and was also found to be suitable for heat transfer measurements in separated flows (discussed in References 6,7 and 8). In the present investigation, the heat transfer measurements were obtained in a shock tube using a number of model configurations and over a range of physical parameters; there are very few measurements of local heat transfer on similar configurations performed in other facilities with which to compare the present data. Some measurements of local heat transfer rates behind a two dimensional and axially symmetric backward facing steps performed in conventional wind tunnels are presented in References 9, 10, 11 and 12, so that comparison between the shock tube measurements and those obtain in the wind tunnel is of particular interest. The main contribution of this comparison may be in providing an indication of the effect of the large differences in the flow stagnation enthalpies in the shock tube vis a vis the wind tunnel and of the effect of the highly cooled boundary layer on the models in the shock tube compared to that of the wind tunnel test conditions. The fact that many of the aspects of the data are comparable, certainly qualitatively, and for some measurements even quantitatively, as will be shown later, is very encouraging and may add to the acceptance of heat transfer measurements in separated flow in the shock tube facility.

An analytical evaluation of the laminar heat transfer variation behind a two-dimensional backward facing step was presented in Ref. 13. This study uses the formulation of the integral conservation equations for evaluation of the heat transfer rate distribution. The calculated heat transfer rates show a growth of a peak in heat transfer in the reattachment zone at increasing Reynolds numbers. In most of the experimental data such a peak is indeed detected.

The results of the analytical calculation and those obtained in shock tube and wind tunnel measurements will be discussed in this paper. The shock tube measurements will be presented first, followed by a discussion of the other measurements and the calculation.

II. THE EXPERIMENTAL APPARATUS

1. The 3" x 3" Shock Tube

The experiments described herein were performed in the 3" x 3" shock tube of the Aerodynamic Laboratory of the Technion's Department of Aeronautical Engineering. The shock tube has a 3 inch diameter 2 meters long high pressure section and a 7 meters long 3" x 3" square low pressure section. This tube is also used to operate a 10" x 12" shock tunnel nozzle. During testing the low pressure section is evacuated to the pressure level required by the test conditions (minimum pressure is approximately 0.7 mm Hg. absolute), the test gas is air in all cases. The driver gas in then introduced to the high pressure

section from high pressure bottled hydrogen or air. The driver pressure is controlled by a copper diaphragm which is scribed to a predetermined depth depending upon the required pressure. The scribing also provides a relatively "clean" break in the copper diaphragm. Further details on the instrumentation for the shock tube operation are described in References 1 - 5.

The local heat transfer rates are measured by the thin platinum film resistance thermometers sputtered on pyrex glass described in References 1 - 5 and in more details in Ref. 14.

2. The Models

The five models used to study the heat transfer in separated flow are shown in Fig. 1. These models have the following base type separated flow geometries: (1) two-dimensional backward facing step, (2) axisymmetric backward facing step, (3) two-dimensional blunt base, (4) sharp protruding leading edge, (5) two-dimensional leading edge separation bubble. The models are made of steel with a pyrex glass insert on which the platinum films are sputtered. The thin film gage are of about 0.5 mm width and are positioned about 1mm to 2mm apart at $\Delta x/h$ values between 0.3 to 10, behind the separation point.

III. TIME OF ESTABLISHMENT OF STEADY CONDITIONS OVER THE SEPARATED ZONES IN THE SHOCK TUBE.

The short test time in the shock tube raises the question of whether or not uniform flow conditions are established in the separated region during the test time available. It has already been shown in the results presented in

References 1 to 8 that steady heat transfer conditions are indeed obtained in the shock tube tunnel tests. The total available test time as a function of the shock Mach number is presented in Fig. 2. The available test time is the time between the passage of the incident shock wave and the arrival of the contact zone disturbances to the model location. It is seen that about 380 microseconds of test time are available at a shock Mach number of 2 and 90 microseconds at a shock Mach number of 10. The duration required to establish steady heat transfer conditions after initiating the flow behind the shock front is determined from the instantaneous heat transfer measurements in the various zones in the separated flow. The longest duration required to establish steady conditions is found to be in the "dead water" zone. It may be seen in Fig. 2, that even in the mixing zone steady conditions are established well within the available test times in the shock tube.

IV. HEAT TRANSFER MEASUREMENTS IN THE SHOCK TUBE EXPERIMENTS

The heat transfer rate measured at each gage position is presented in terms of the parameter, $Nu_x/PrRe_x^{1/2}$, and is plotted as a function of distance behind the separation point, $\Delta x/h$, in Fugures 3, 4, 5 and 6 for the two dimensional and axially symmetric steps, the sharp protruding leading edge and the leading edge separation bubble, respectively. In these shock tube tests both the initial pressure and shock Mach number are varied, therefore the flow Mach number, Reynolds number and the stagnation to wall enthalpy ratio are varied simultaneously. The data obtained in these shock tube experiments must be examined as a function of

the various test conditions so that the effects dominating the heat transfer in the separated flow can be found.

The variations of the local heat transfer rates measured behind a two-dimensional step are presented in Fig. 3. These measurements show a low heat transfer rate in the dead water zone then an increasing heat transfer rate towards the reattachment zone where relatively high values are obtained. Further downstream the heat transfer rate is reduced again towards an asymptotic value which may be about equal to or even higher than the flat plate result. The maximum heat transfer rate in the reattachment zone behind the two dimensional backward facing step is found to increase with increasing Reynolds number. In these tests the flow Mach number, M_f, is varied between 1.8 to 2.6 and the enthalpy ratios, h_{se}/h_w are about 30 to 50. These variations seem to have only a small effect on the parameter $Nu_x/PrRe_x^{1/2}$ since all this data can be correlated with relatively small scatter by the parameters Re_h and $hRe^{1/2}/L$, as shown in Figures 8 and 9.

The positions of the heat transfer peak behind the two dimensional step are found to be at a distance of about 4 to 5 heights behind the step. These positions are within the reattachment zone as indicated in Ref. 1. The value of the maximum heat transfer rate as a function of position behind the separation point is plotted in Fig. 10.

The heat transfer rates measured behind the axially symmetric backward facing step (Ref. 2) are shown in Fig. 4. The heat transfer distribution behind

the step is qualitatively similar to that found in the two dimensional case. A maximum value of heat transfer rate is clearly obtain and can be correlated with the Reynolds number variation. The maximum heat transfer rate is located at about 5 to 6 step heights, as is indicated in Fig. 10.

The sharp protruding leading edge model is of particular interest since the separated flow over this model starts at the leading edge with about zero initial boundary layer thickness. The model for the generation of this type of a separated flow was suggested by R.D. Chapman (Ref. 15). This model is used then for estimation of the pressure in the separated zone and also to obtain experimentally the pressure profile of this well defined shear layer in the region of reattachment to the surface. The heat transfer measurements in this case are discussed in Ref. 4 and shown in Fig. 5. Here again the variation of the local heat transfer rate is qualitatively similar to that obtain behind the backward facing step. It is interesting to note that the separated zone in this case is longer than the one obtained in the case of a backwrad facing step, with a comparable step height where an initial boundary layer is present. In the protruding leading edge model case, the maximum heat transfer rate is found to be at about 8 step heights behind the separation point, and the value of the maximum heat transfer rate is significantly lower than that for the two-dimensional backward facing step. This result, and the other results plotted in Fig. 10, suggest that the longer the mixing zone the lower the maximum heat transfer at reattachment.

Measurements of heat transfer in the leading edge separation bubble reported in Ref. 5 are shown in Fig. 6. Here again the heat transfer rate just behind separation is very low and increases towards reattachment.

Measurements of the heat transfer rate on the blunt two dimensional base are presented in Ref. 3 and are included in Figures 7, 8 and 9. In the blunt base case, the maximum heat transfer rate which is found at the base center, is of particular interest for the design of base heat shields. This maximum value is relatively low at low Reynolds numbers but, at high Reynolds numbers may even be slightly higher than the flat plate value as indicated in Figures 7 to 9.

V. DISCUSSION OF THE HEAT TRANSFER RATE MEASUREMENTS AND COMPARISON WITH OTHER EXPERIMENTAL RESULTS.

Summary of the results of measurements of the maximum heat transfer rates for the base type separated flows are presented in Figs. 7, 8 and 9. The maximum heat transfer rate variations as a function of the flow Mach number, M_f, in the shock tube is presented in Fig. 7. It should be remembered here that while the flow Mach number decreased from about 2.6 to 1.8 the Reynolds number Re_L is increased in these tests from about 10^3 to about 2×10^5 and, as discussed previously, we expect that most of the increase in the maximum heat transfer rates is due to this increase in Re_L rather than due to the effect of the flow Mach number variation. This becomes more evident when the data is plotted as functions of Reynolds number dependent parameters as in Figs. 8 and 9. The data

is plotted as a function of Re_h in Fig. 8 and as a function of $hRe_L^{1/2}/L$ in Fig. 9. It was shown in Ref. 16, that the pressure in a separated flow can be correlated in the case of a very thin boundary layer at separation, i.e. $\delta_s \rightarrow 0$, as a function Re_h. In the present shock tube tests, the boundary layer on the models is expected to be very thin due to the effect of the extremely cold wall conditions. In this case it may be expected that the maximum heat transfer rate will correlate relatively well in terms of Re_h. However, when initial boundary layer effects are more dominant, as in the two-dimensional and axially symmetric backward facing step case, better correlation is obtained when heat transfer data is plotted as a function of a δ_s/h related parameter i.e. $(hRe_L^{1/2}/L)$ as shown in Fig. 9. The following relations correlate the data obtained in the shock tube experiments:

For cases with an initial boundary layer at separation,

$$q/q_{f.p} = A(hRe_L^{1/2}/L)^n \tag{1}$$

For cases of a very thin ("zero") initial boundary layer at separation,

$$q/q_{f.p} = B\, Re_h^m \tag{2}$$

The empirical parameters, A, B, m and n for the various separated flow geometries are presented in Tables 2 and 3. It was found that these forms of relations can also be used for representation of the average heat transfer rate in the separated flows measured in our tests. The values of the parameters for the evaluation of the average heat transfer rates are also presented in Tables 2 and 3.

In spite of the large interest in heat transfer in separated flows there are relatively few measurements of local heat transfer rates in such flows. Most of the available measurements are also limited to very few (sometime only one or two) flow conditions in each investigation. It is therefore difficult to systematically compare the results. However, in the following discussion we will try to include whatever significant results that can be drawn out of available measurements. In addition to the already discussed shock tube experiments, heat transfer in base type separated flows were measured by: Sanford and Ginoux (Ref. 9 - two-dimensional backward facing step) Baker and Martin (Ref. 10 - two-dimensional backward facing step), Naysmith (Ref. 11 - two-dimensional and axially symmetric backward facing steps),Thomann (Ref. 12- two-dimensional backward facing step and spoiler in turbulent separation), Bogdonoff and Vas (Ref. 17 - conical separation due to a spike) and by Bloom and Pallone (Ref. 18 - cylindrical perturbances). The results obtained in these investigations indicate, in almost all cases, a peak heat transfer rate in the reattachment zone. It is therefore interesting to compile the measured peak heat transfer rates and plot them as a function of the position where these peaks occur, as is shown in Fig. 10. The data of Sanford and Ginoux (Ref. 9) did not indicate any peak in heat transfer expect in the case of transitional or turbulent reattachment. It is suggested in Ref. 9 that the peaks in the heat transfer rate at reattachment occur only if transition occurs ahead of reattachment. Although results of most of the measurements support the conjecture that transition in the shear layer enhances the heat transfer at reattachment (particularly shown in the

results of References 1 and 10), the fact that in many other investigations peaks in heat transfer were detected even at Reynolds numbers where the flow is expected to be laminar may indicate that a peak in heat transfer rate can be also associated with the reattachment of the laminar shear layer to a surface. This is well illustrated in the heat transfer measurements of Bogdonoff and Vas (Ref. 17). They reported the measurements of the heat transfer of the reattachment zone due to a shear layer generated by spikes of various lengths on a hemispherical nose. These measurements were conducted in a Helium wind tunnel at M = 14 and Reynolds numbers of 3×10^5 to 2×10^6 based on the spike length. At these conditions the shear layer should be completely laminar. They found that although the heat transfer to the stagnation region was greatly reduced, the heat transfer to the rear part of the hemisphere, where the reattachment occurs is greatly increased. The highest values of heat transfer in the reattachment zone were obtained with the short spike, then, as the spike length was increased, the heat transfer rates decreased. The measurements with the presence of the spike, normalized by the value of the heat transfer to that portion of the hemisphere when measured without a spike, are included in Fig. 10 as well. The results obtained in this case seem to describe well the trend presented by the data plotted in Fig. 10 from all the various investigations at Mach numbers varying from low supersonic Mach numbers in the shock tube to hypersonic Mach numbers of up to 14 obtained in the Helium wind tunnel. It may be therefore stated' that the experimental results indicate that peaks in heat transfer occur in the reattachment zone in laminar as well as transitional and turbulent flows. It is also shown that the shorter the shear layer in the mixing

zone of the separated flow, the higher the value of the maximum heat transfer rate at reattachment. This variation of the peak in the heat transfer rate may be attributed to the fact that the shear layer is also thinner for the cases of the short mixing layers. This observation is in line with the previously observed pressure variation in separated flows where it was found that, the shallower and, therefore, the longer the mixing zone, the higher is the base pressure. Now, the length of the separated zone has been found to depend mainly on the Reynolds number of the flow and the state of the mixing in the shear layer (laminar, transitional or turbulent). It is therefore also reasonable to expect that the heat transfer rate will be dependent mainly on the Reynolds number as indeed is suggested by the present measurements. Furthermore, most of the effects of the Mach number and of the stagnation tc wall enthalpy ratio, which are varied over a wide range in the discussed experiments, result in the variation of the length of the mixing zone and the position of reattachment. Therefore, the inverse relation between the maximum heat transfer at reattachment and the distance between the separation point to the position of this peak is physically plausible. Such a relation is evident from the data collected in Fig. 10. Some of these hypotheses are in agreement with the results of an analytical calculation of Reference 13 which will be presented.

VI. COMPARISON OF THE EXPERIMENTAL DATA WITH A CALCULATION OF THE HEAT TRANSFER RATE BEHIND THE TWO DIMENSIONAL STEP.

A method based on the use of the integral conservation equations for the calculation of heat transfer distribution behind a two dimensional backward facing step was presented by Seginer and Rom in Ref. 13. The formulation of the

equations follows the Crocco-Lees integral analysis modified to include heat transfer effects. A short resume of this method will be presented here in order to facilitate the discussion concerning the comparison of these analytical calculations with the experimental data.

Using a model of the flow field shown in Fig. 11, the integral conservation equations can be written (following the assumptions and notation of Ref. 13):

$$dm/dx = \rho_e u_e a_s [d\delta/dx - \Theta] = p/\phi_e [d\delta/dx - \Theta] \tag{3}$$

and

$$K = (d\delta/dx - \Theta)$$

$$(d/dx)(m\kappa_u w_e) = w_e(dm/dx) - \delta(dp/dx) - [(pw_e)/\phi_e](c_f/2) \tag{4}$$

$$(d/dx)(m\kappa_h) = dm/dx + (p/\phi_e)c_q \tag{5}$$

where

$$\kappa_u = \frac{I}{\bar{m}u_e} = (\delta - \delta^* - \delta^{**})/(\delta - \delta^*) \tag{6}$$

$$\kappa_h = \frac{H}{\bar{m}h_{se}} = (\delta - \delta^* + \delta^{***})/(\delta - \delta^*) \tag{7}$$

where we define

$$\bar{m} = \int_0^\delta \rho u dy \; ; \quad I = \int_0^\delta \rho u^2 dy \quad \text{and} \quad H = \int_0^\delta h_s \rho u dy$$

and c_f and c_q are the friction and heat transfer coefficients respectively.

The equations for the external flow are:

$$m = (p\delta)/\phi_1 \tag{8}$$

$$dp/p = - (dw_e/\phi_e) \tag{9}$$

$$\Theta = \Theta(w_e) \tag{10}$$

where

$$\phi_e = (T_e/T_{se})(1/\gamma w_e)$$

and

$$\phi_1 = (T_1/T_{se})(1/\gamma w_1)$$

The conservation equations (Eqs. 3, 4 and 5) and the external flow equations (Eqs. 8, 9 and 10) with the additional correlation functions for c_f, c_q, K and ϕ_1 enable a complete mathematical formulation of the problem. Since the correlation relations between the various parameters must be obtained from independent analysis or empirical data, the present analysis is limited to cases where such correlation functions are available or can be speculated. In our case of separated flows with heat transfer there is only very limited experimental data to guide the selection of the correlation functions. In Reference 13 the variation of the correlation functions in cases of attached flows with pressure gradients and heat transfer were studied. Based on the results of these calculations, the correlation function variation in the separated flow behind a two-dimensional step shown in Fig. 12 were selected.

These correlation functions are defined as follows:

The heat transfer correlation function

$$B(\kappa_u) = c_q/\{Pr^{-2/3}[(h_u/h_{se})-r](\mu_e/\bar{m})\} \tag{11}$$

The mass correlation function

$$C(\kappa_u) = K \cdot (\bar{m}/\mu_e) \tag{12}$$

and the friction correlation function

$$D(\kappa_u) = c_f \cdot (\bar{m}/\mu_e) \tag{13}$$

The pressure distribution behind a two dimensional backward facing step was measured and can be approximated in a simplified form as shown in Fig. 13. Using this pressure variation and the correlation functions presented in Fig. 12, the heat transfer variation behind a backward facing step can be calculated. The results obtained in Ref. 13 for flow conditions corresponding to those of the shock tube experiments of Ref. 1 are presenred in Fig. 4. These heat transfer measurements are very similar qualitatively to those obtained in the measurements of Ref. 1, which are reproduced in Fig. 15. Better quantitative agreement can be obtained by appropriate modification to the correlation functions used in the calculation of Ref. 13. The appearance of peaks in the heat transfer rates in the reattachment zone at increased Re_L in this calculation suggest that these peaks (obtained also in the many experimental investigations) are associated with the recompression mechanism at reattachment. It is seen from Fig. 13 that the pressure rise at reattachment steepens with increasing Re_L. The peak in the heat transfer rates obtained in the calculation may be due to the sharp rise in the pressure at reattachment.

VII. CONCLUSIONS

The local heat transfer rate measurements in base type separated flows indicate heat transfer rates which are low in the "dead-water" zone, increase to a maximum in the reattachment zone and then decrease to an asymptotic value downstream of reattachment.

The value of the maximum heat transfer rate in the reattachment is increased with increasing Reynolds number for a fixed geometry separated flow. It seems that the peak of the heat transfer rate becomes very high, about 7 to 10 times flat plate value, when the transition appears ahead of reattachment. The results of many investigations indicate that when the shear layer in the mixing zone of the separated flow becomes shorter, and therefore this shear layer is also thinner at reattachment, then the value of the maximum heat transfer rate at reattachment is found to increase considerably. The data of the various investigations indicate generally an inverse relation between the maximum heat transfer rate at reattachment and the distance from the separation point to the position of this peak.

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TABLE 1

MODEL CHARACTERISTICS AND TEST CONDITIONS

	Two-Dimensional Backward Facing Step	Axisymmetric Backward Facing Step	Two-Dimensional Blunt Base	Sharp Protruding Leading Edge	Two-Dimensional Leading Edge Bubble
h(mm)	1.55	1.9	2.83	1.48	-
L(mm)	14	17	41.09	0	0
M_s	4 - 10	2.5 - 10	2.6 - 11	2.3 - 10	2.5 - 10
M_f	1.5 - 2.7	1.0 - 2.7	1.0 - 2.7	0.5 - 2.6	0.4 - 2.7
Re_h	$2x10^3$ - $6x10^4$	$2.4x10^3$ - $2x10^5$	$5x10^3$ - $5x10^5$	$3x10^2$ - $1.7x10^4$	$8x10^2$ - $3.3x10^4$
Re_x	$2.5x10^3$ - $3.4x10^5$	$2.4x10^3$ - $3.3x10^5$		$7x10^2$ - $2.9x10^5$	$1x10^3$ - $1.5x10^4$

TABLE 2

AVERAGE AND MAXIMUM HEAT TRANSFER RATE PARAMETERS FOR CASES WITH INITIAL BOUNDARY LAYER.

$$q = A(hRe_L^{1/2}/L)^n \, q_{f.p.}$$

	$q_{ave}/q_{f.p.}$		$q_{max}/q_{f.p.}$	
	A	n	A	n
Two-Dimensional Backward Facing Step	0.02	1.2	0.0465	1.3
Axially Symmetric Backward Facing Step	0.037	1.0	0.068	1.0
Two-Dimensional Blunt Base	0.018	0.77	0.034	0.7

TABLE 3

AVERAGE AND MAXIMUM HEAT TRANSFER RATE PARAMETERS FOR CASES WITH ZERO BOUNDARY LAYER AT SEPARATION

$$q = B \, Re_h^m \, q_{f.p.}$$

	$q_{ave}/q_{f.p.}$		$q_{max}/q_{f.p.}$	
	B	m	B	m
Sharp Protruding Leading Edge	0.04	0.27	0.057	0.34
Leading Edge Separation Bubble	0.0057	0.45	0.0076	0.45

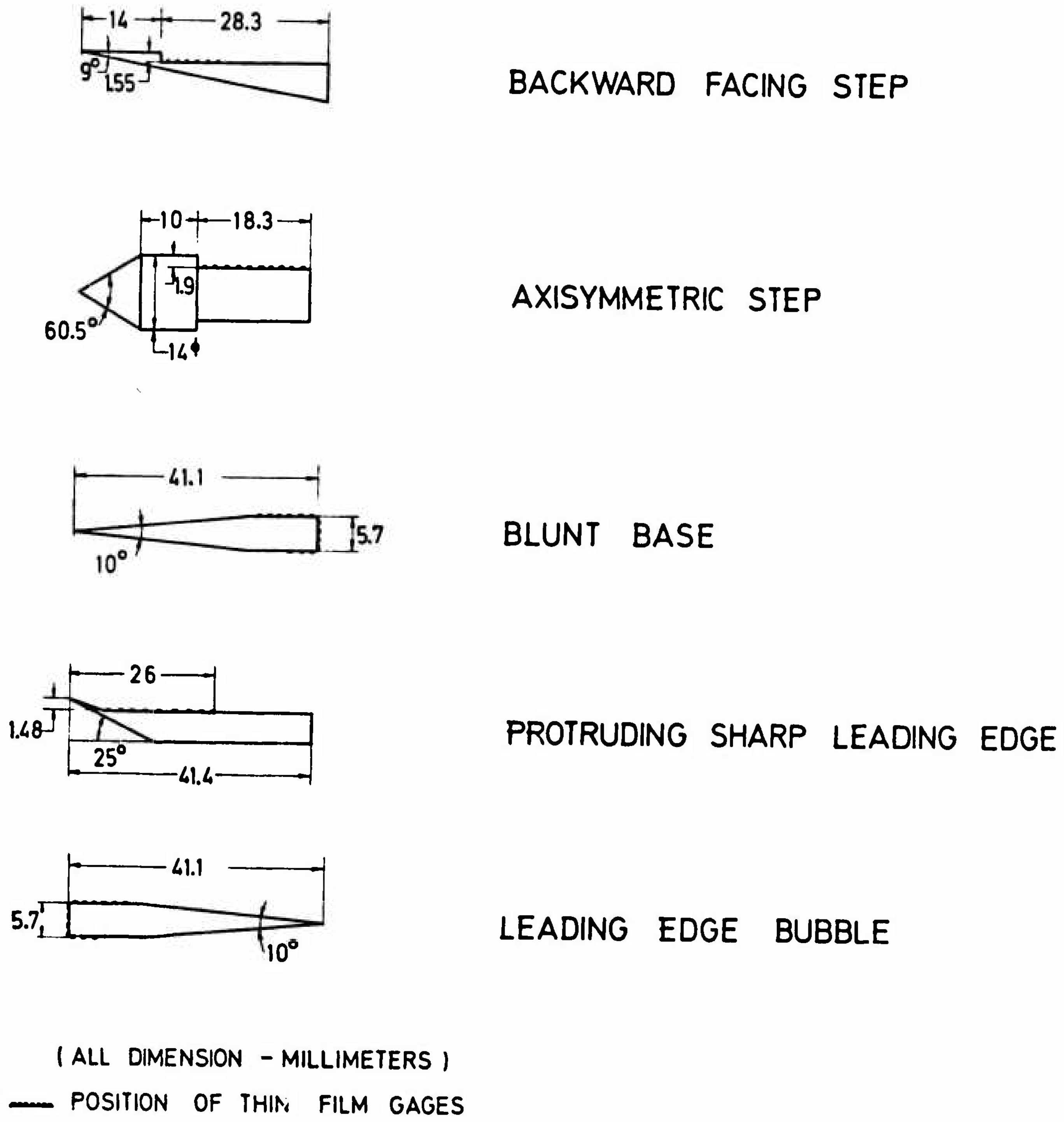

FIG. 1 Models of base type separated flows used in the shock tube experiments.

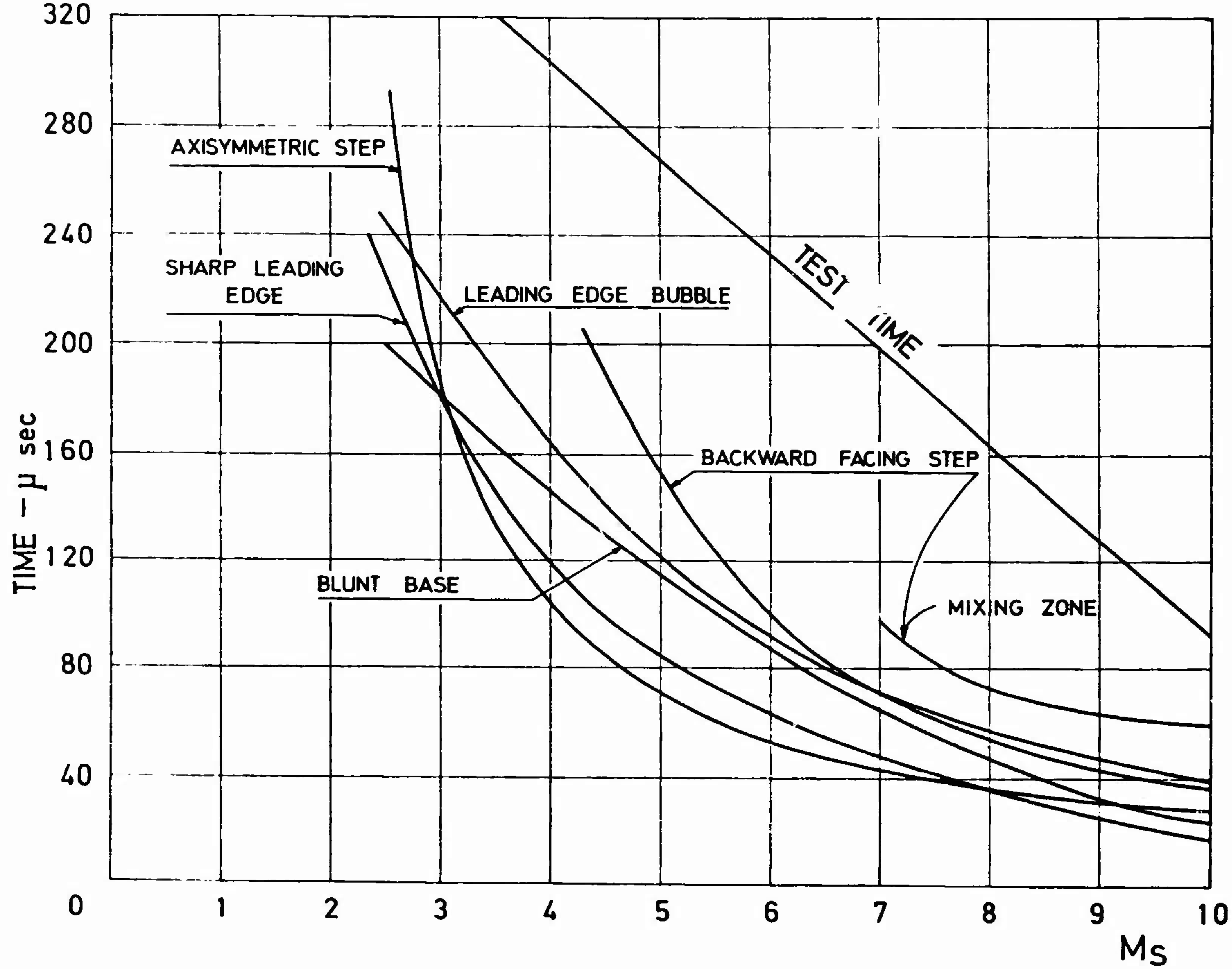

FIG. 2 Time for establishment of steady conditions in the separated flow.

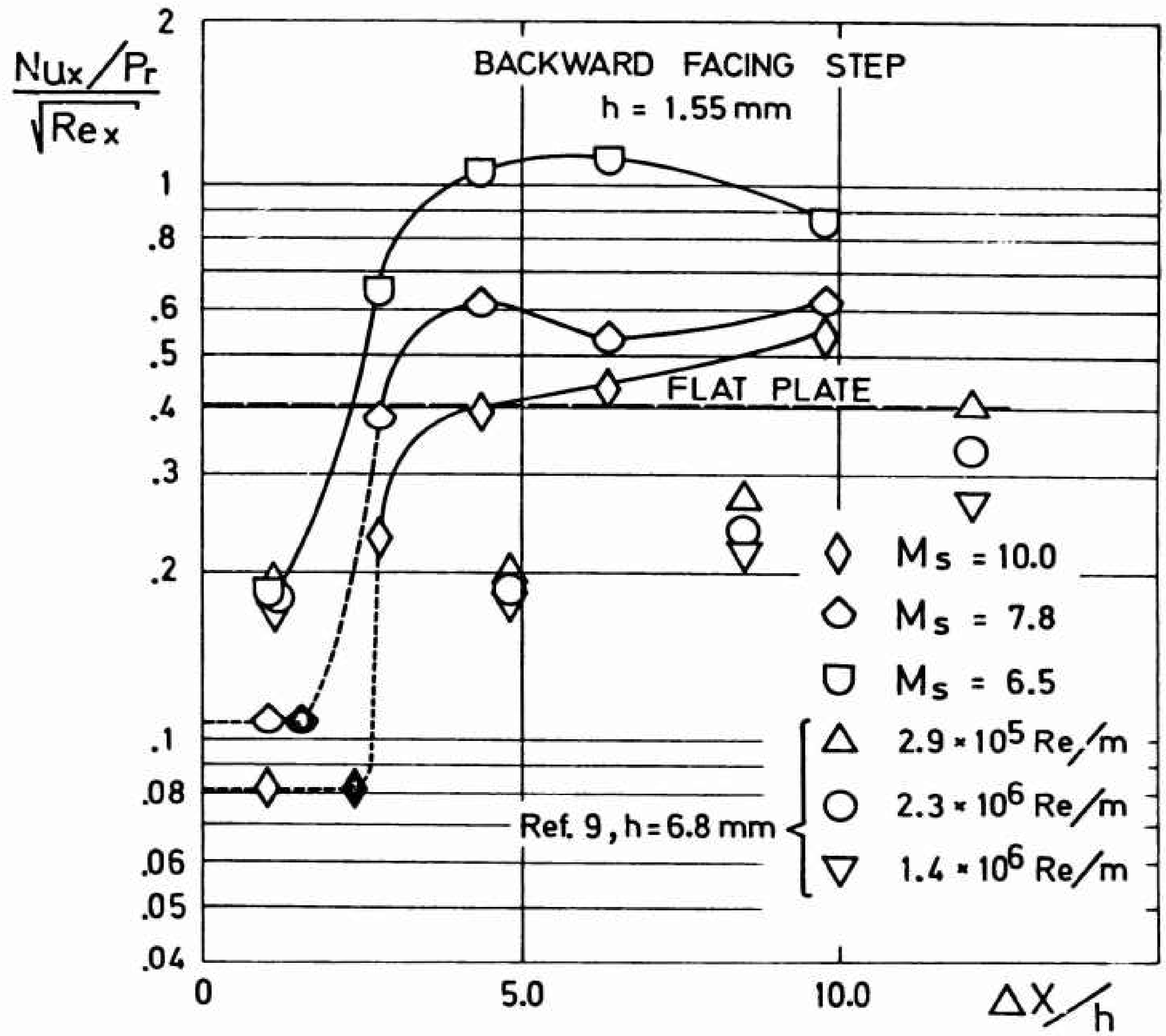

FIG. 3 $Nu_x/Pr\ Re_x^{1/2}$ as a function of $\Delta x/h$ for the two-dimensional backward facing step model.

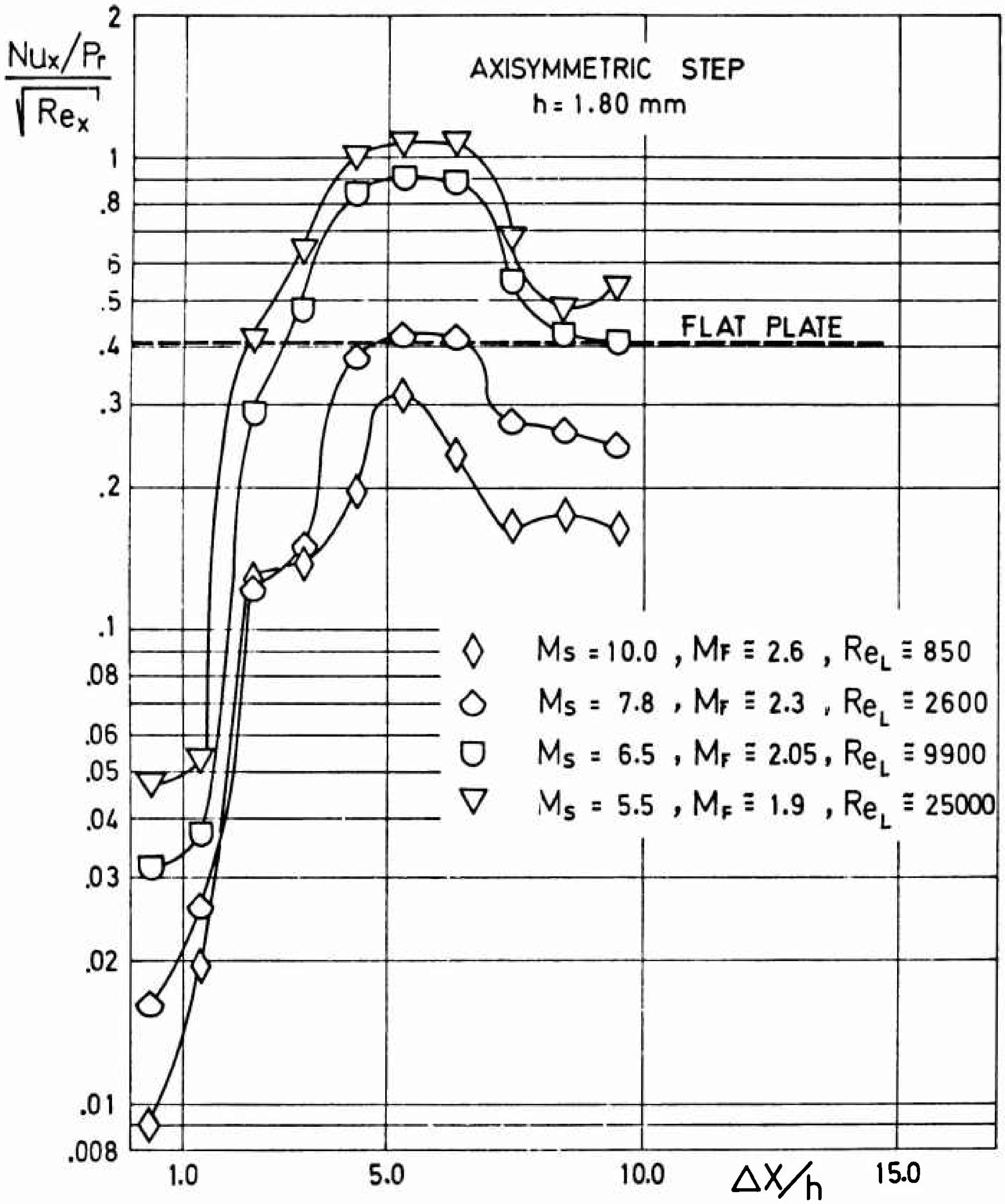

FIG. 4 $Nu_x/Pr\ Re_x^{1/2}$ as a function of $\Delta x/h$ for the axially symmetric step model.

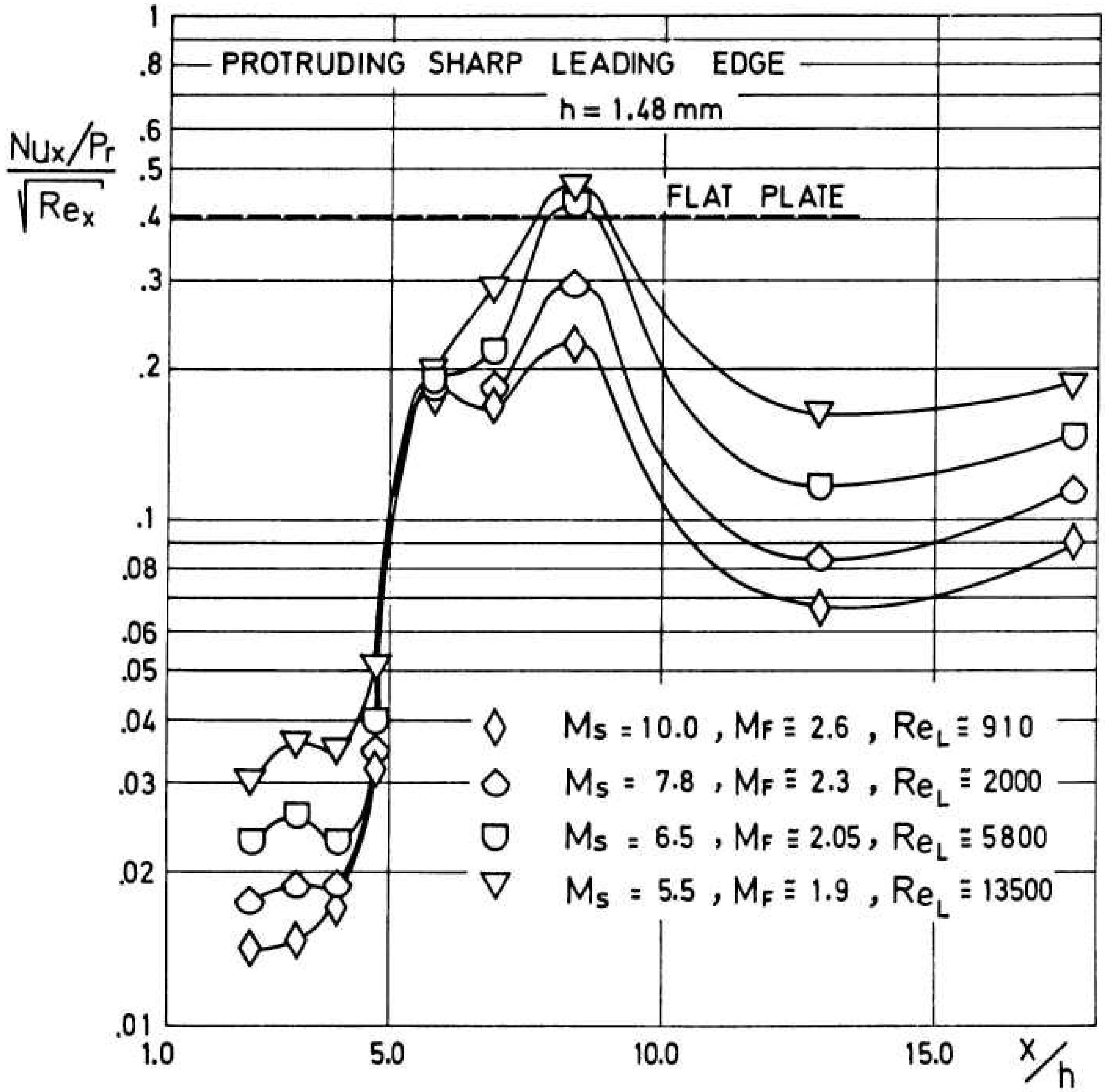

FIG. 5 $Nu_x/Pr\ Re_x^{1/2}$ as a function of $\Delta x/h$ for the protruding leading edge model.

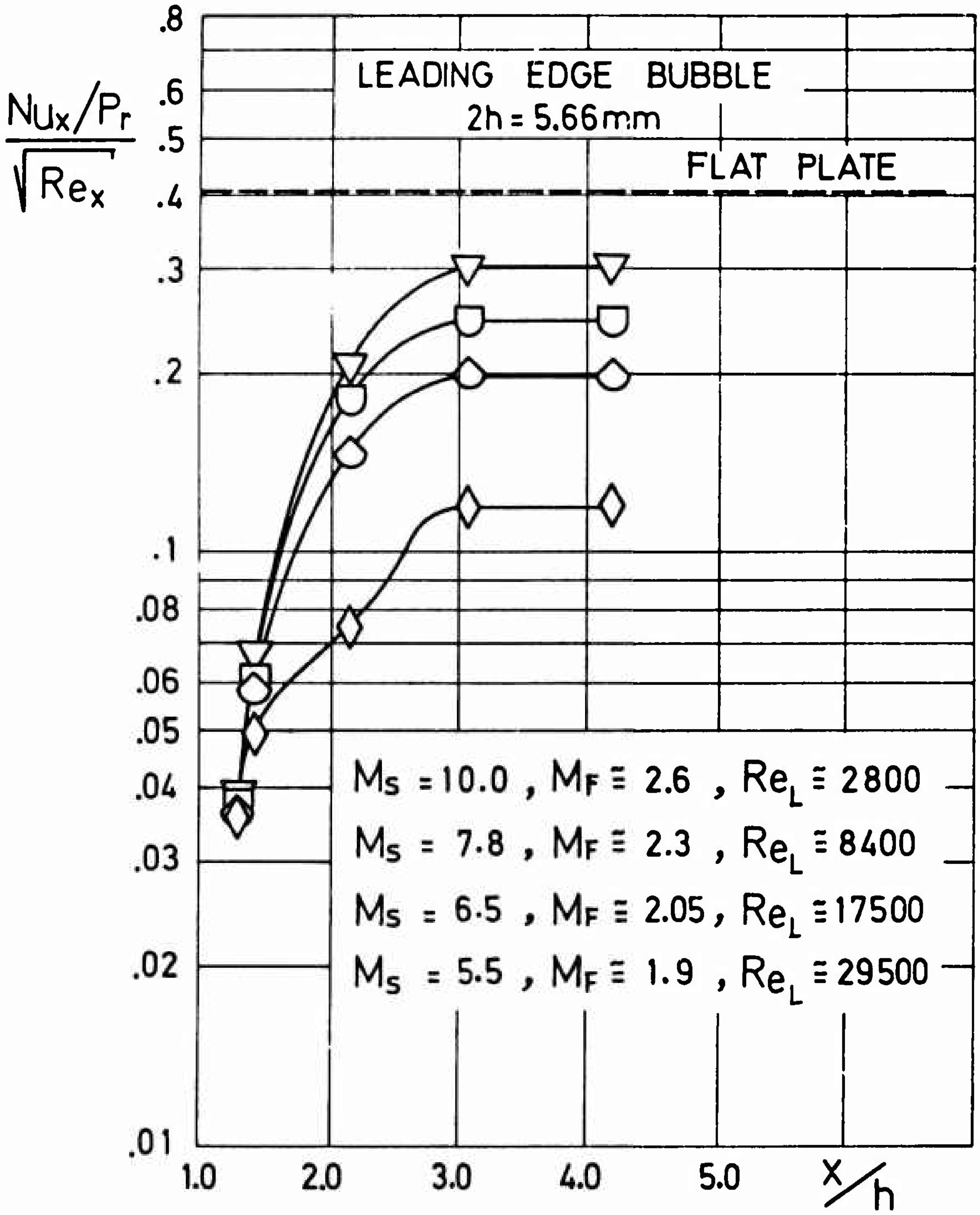

FIG. 6 $Nu_x/Pr\ Re_x^{1/2}$ as a function of $\Delta x/h$ for the leading edge separation bubble model.

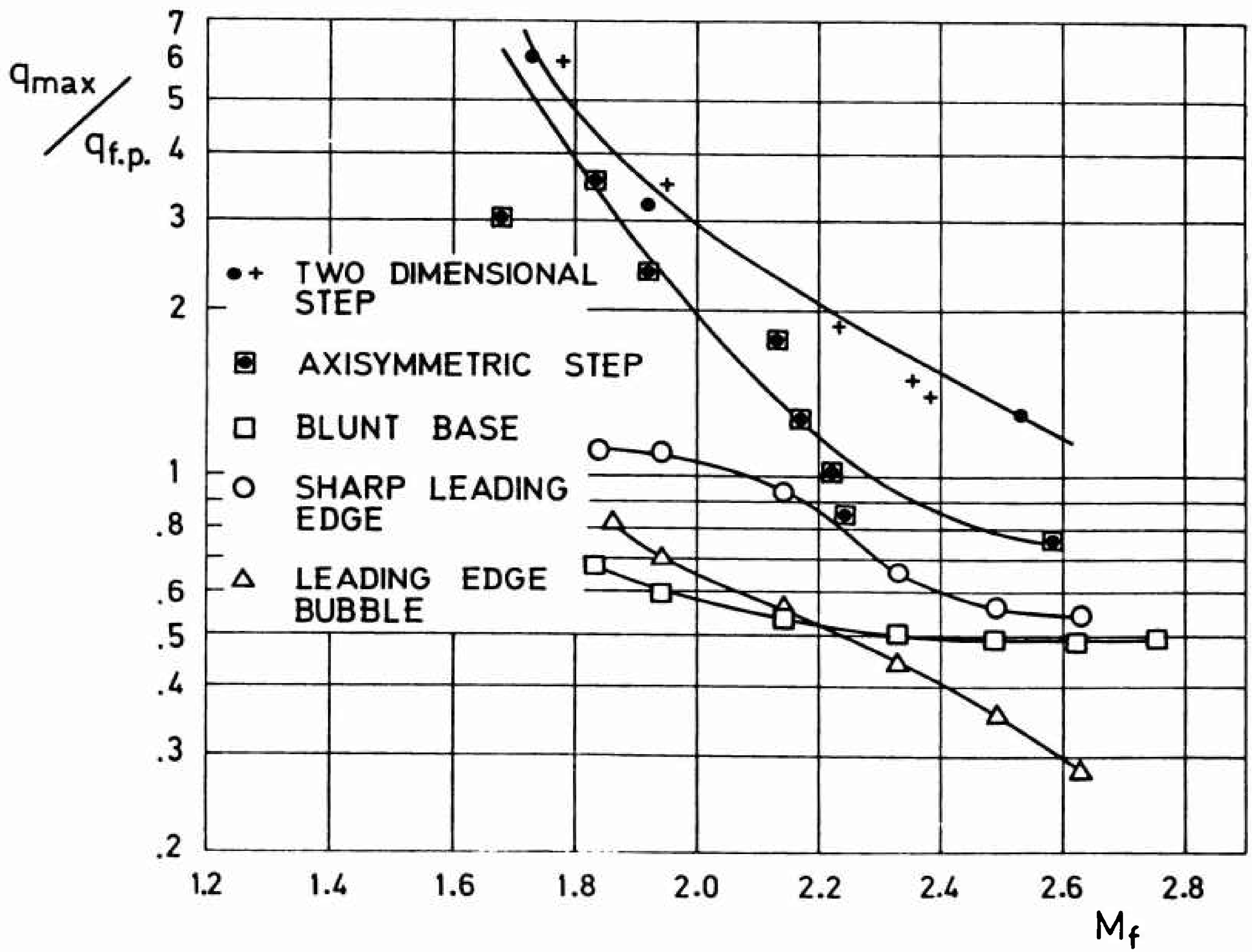

FIG. 7 Maximum heat transfer rate at reattachment as a function of M_f.

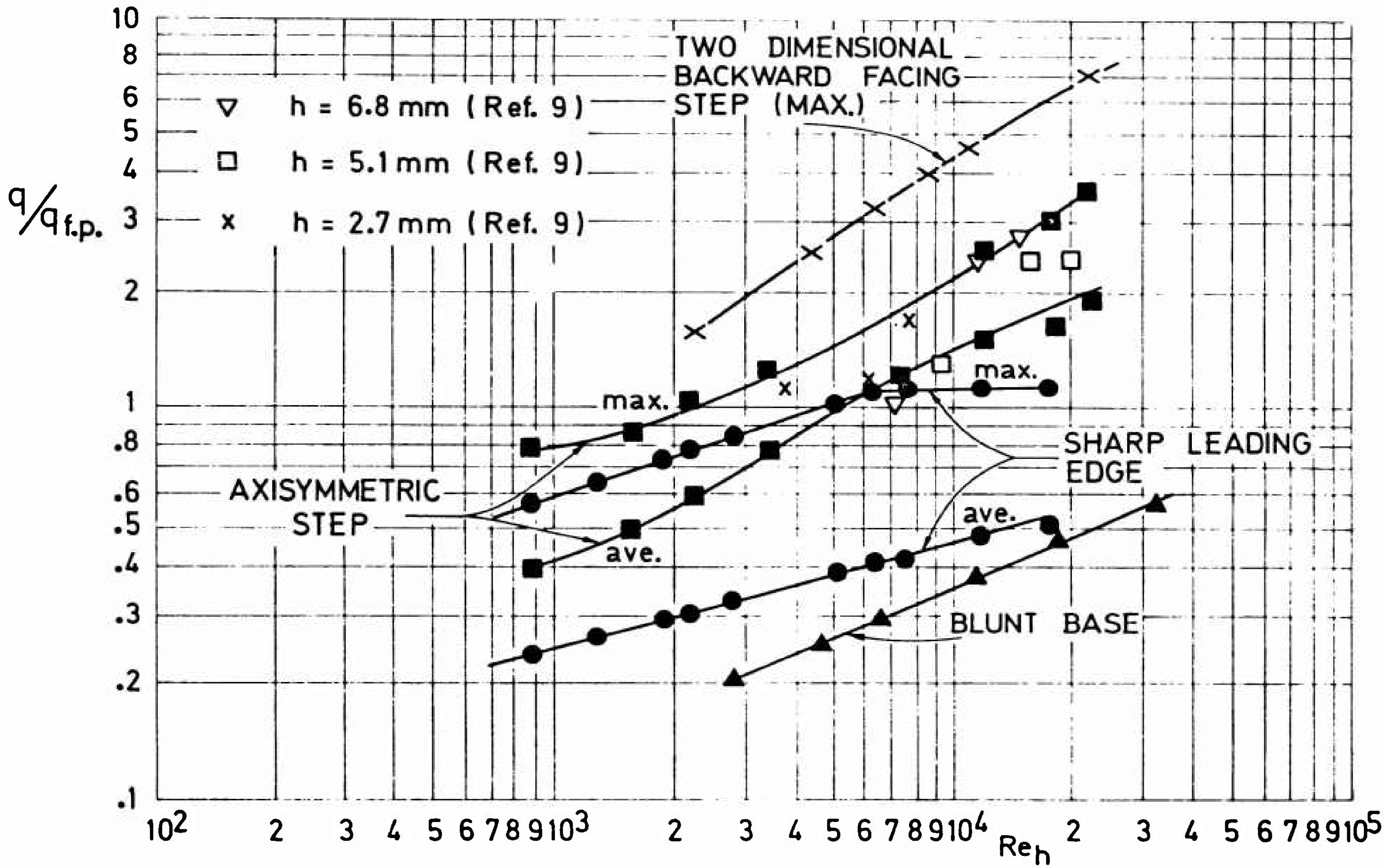

FIG. 8 Maximum and average heat transfer rates as a function of Re_h.

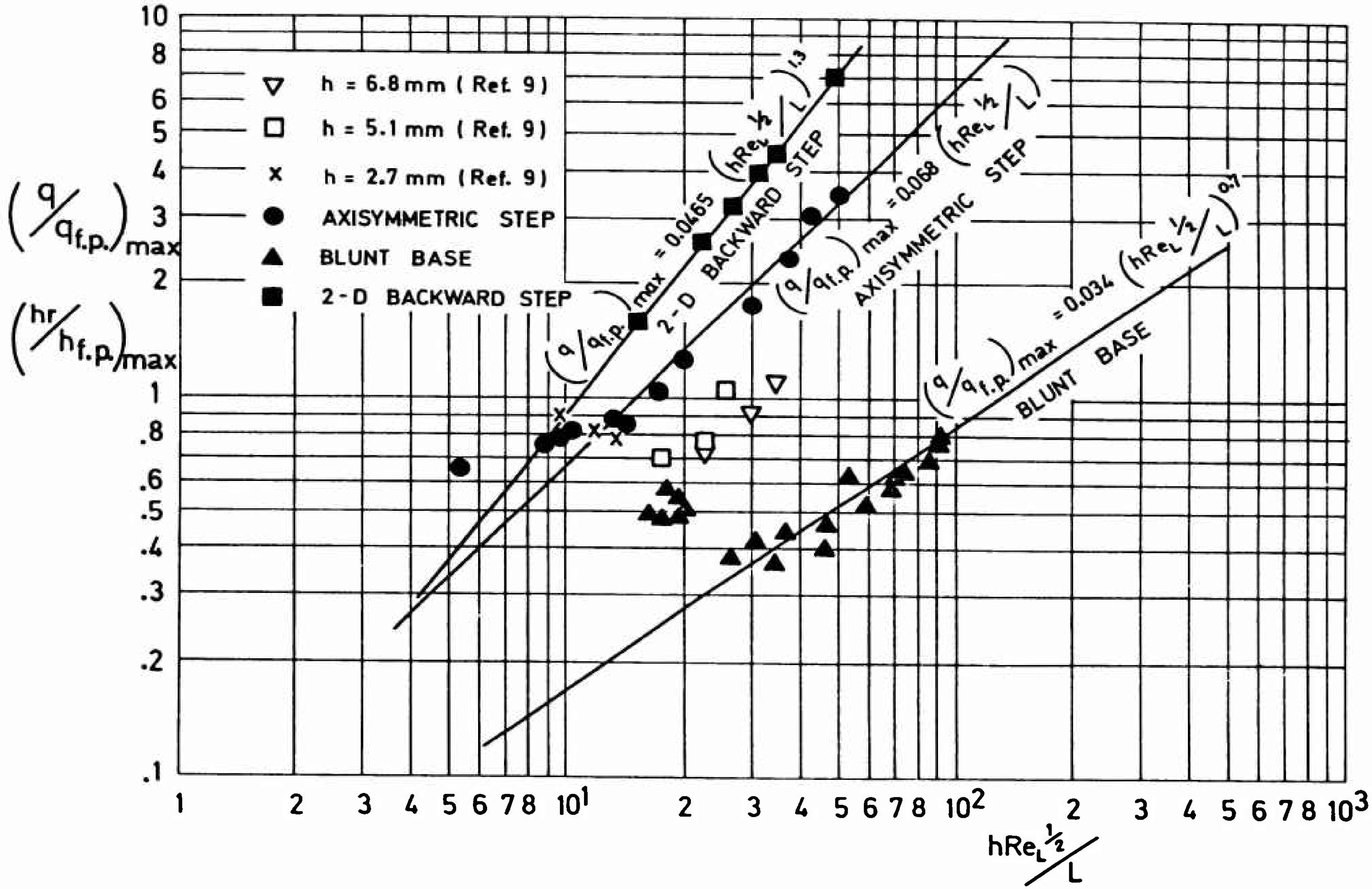

FIG. 9 Maximum and average heat transfer rates as a function of $hRe_L^{1/2}/L$.

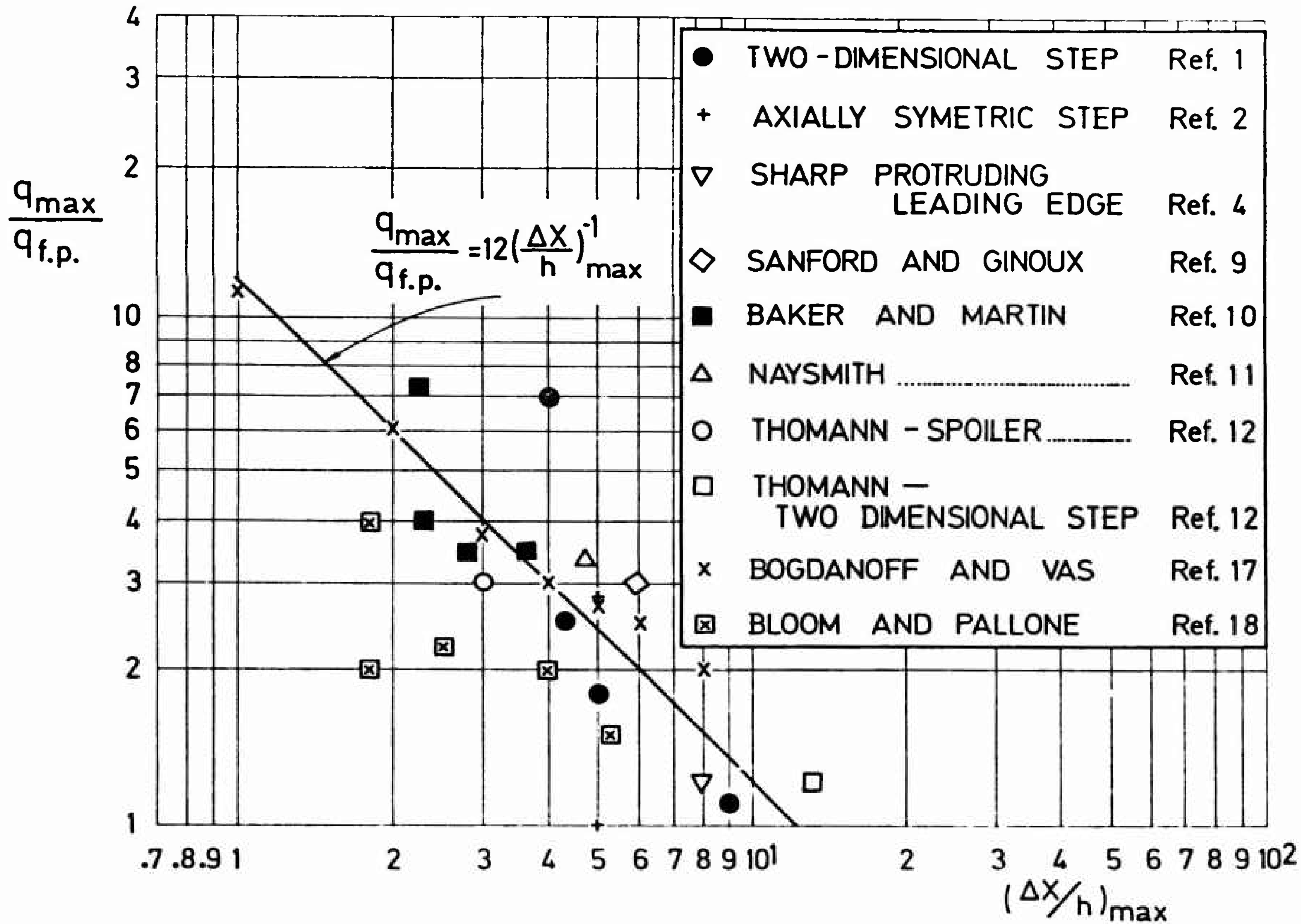

FIG. 10 Maximum heat transfer at reattachment as a function of $(\Delta x/h)_{max}$.

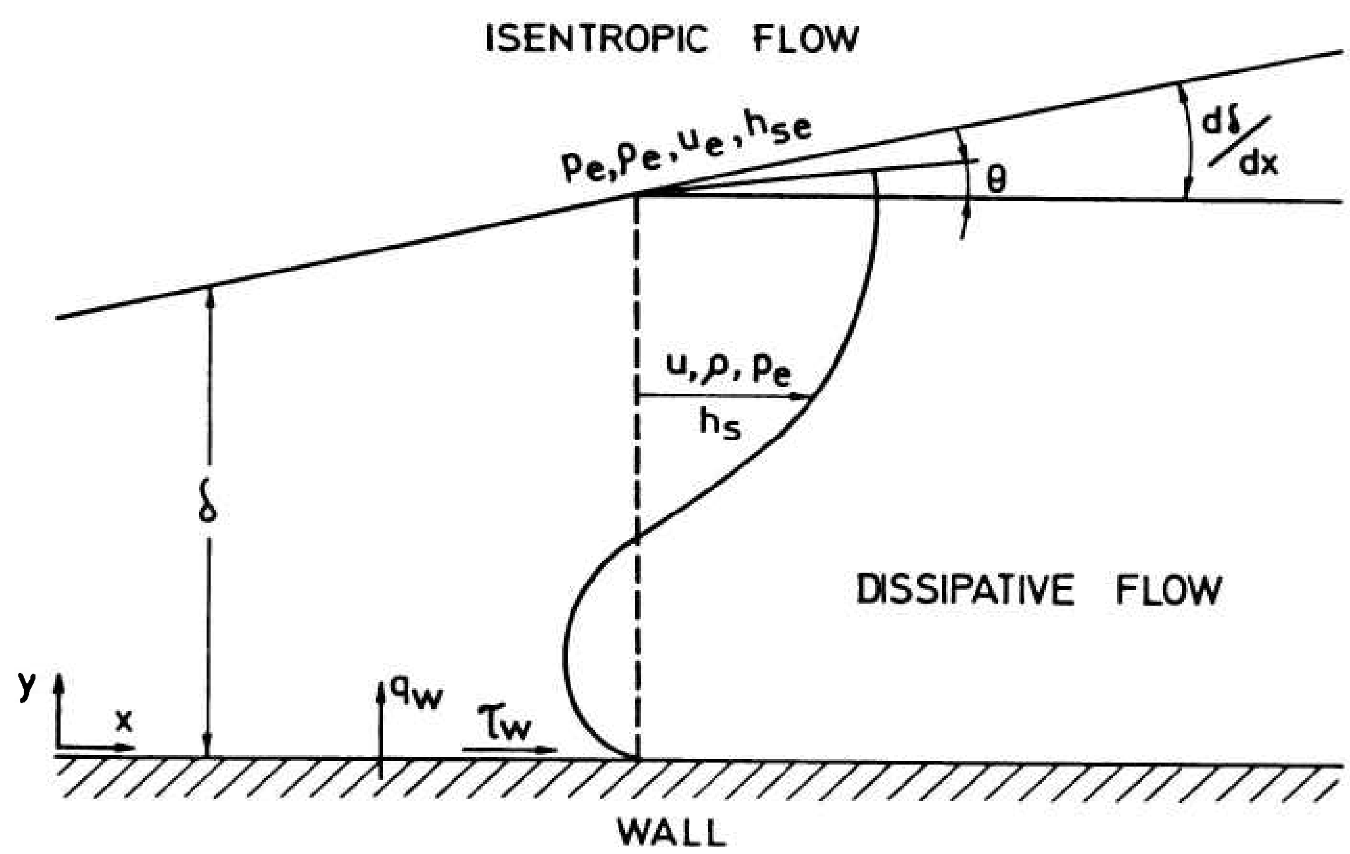

FIG. 11 Model of the dissipative flow for the integral formulation.

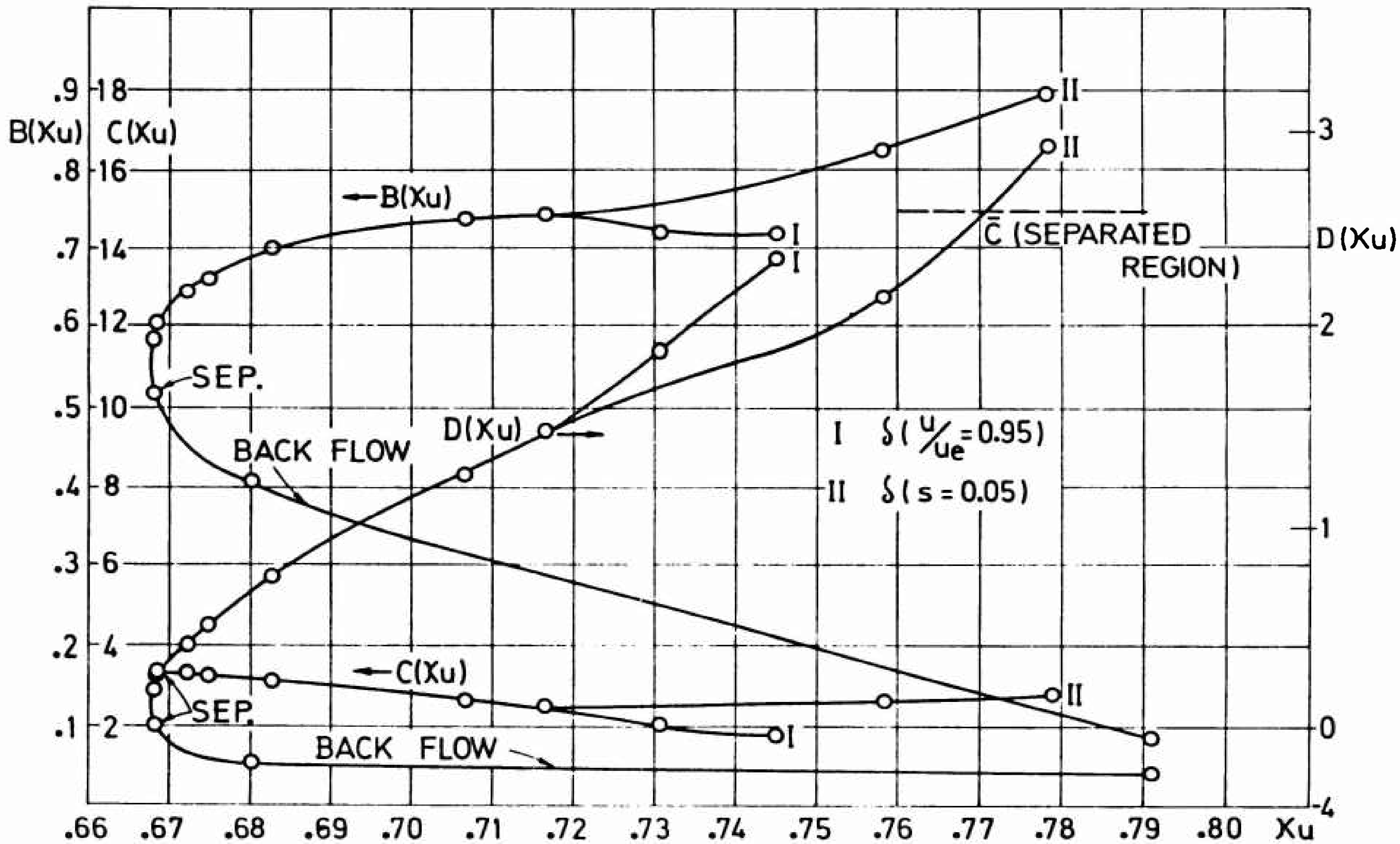

FIG. 1? The correlation functions for laminar separated flow.

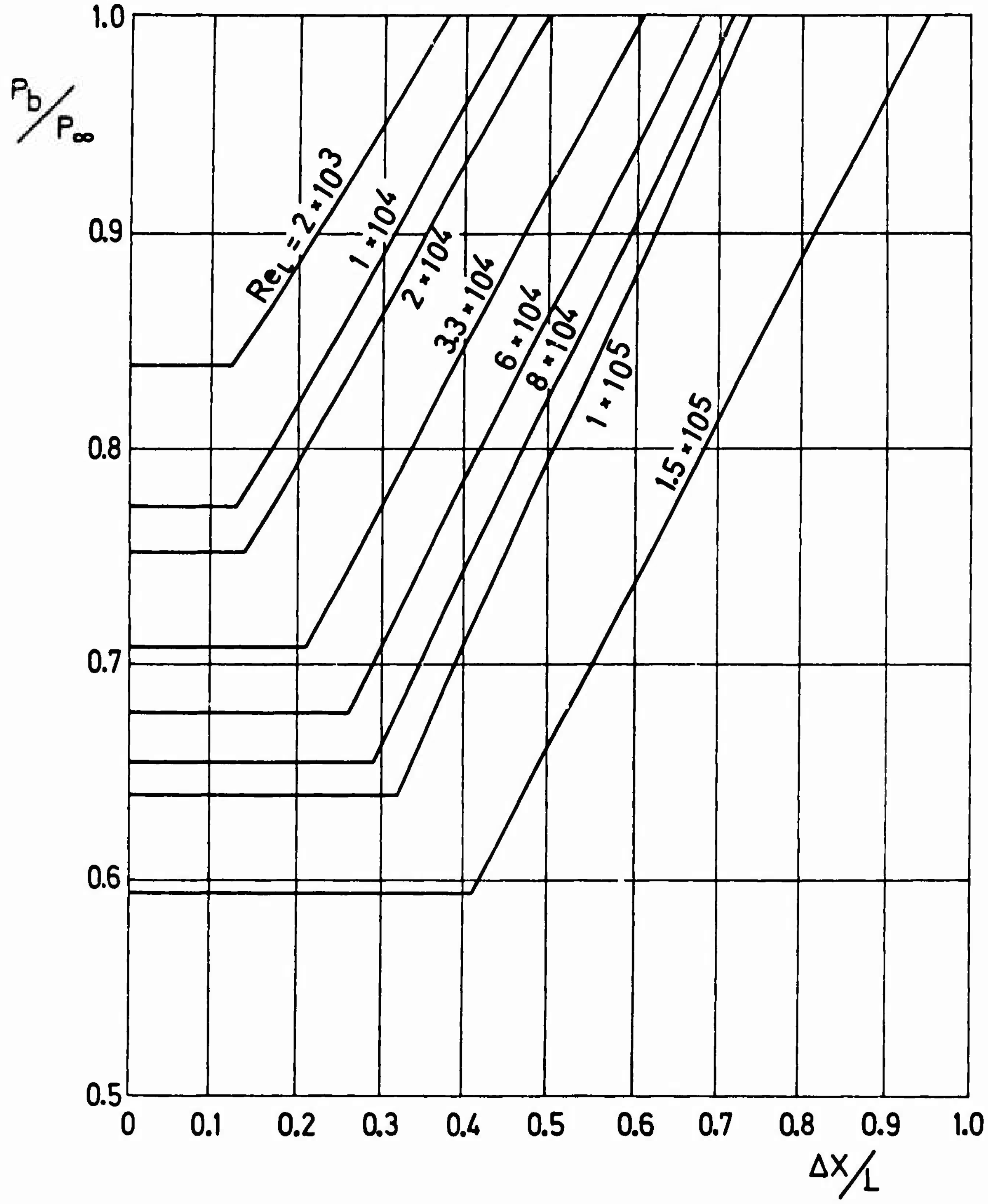

FIG. 13 Simplified pressure distributions behind a backward facing step.

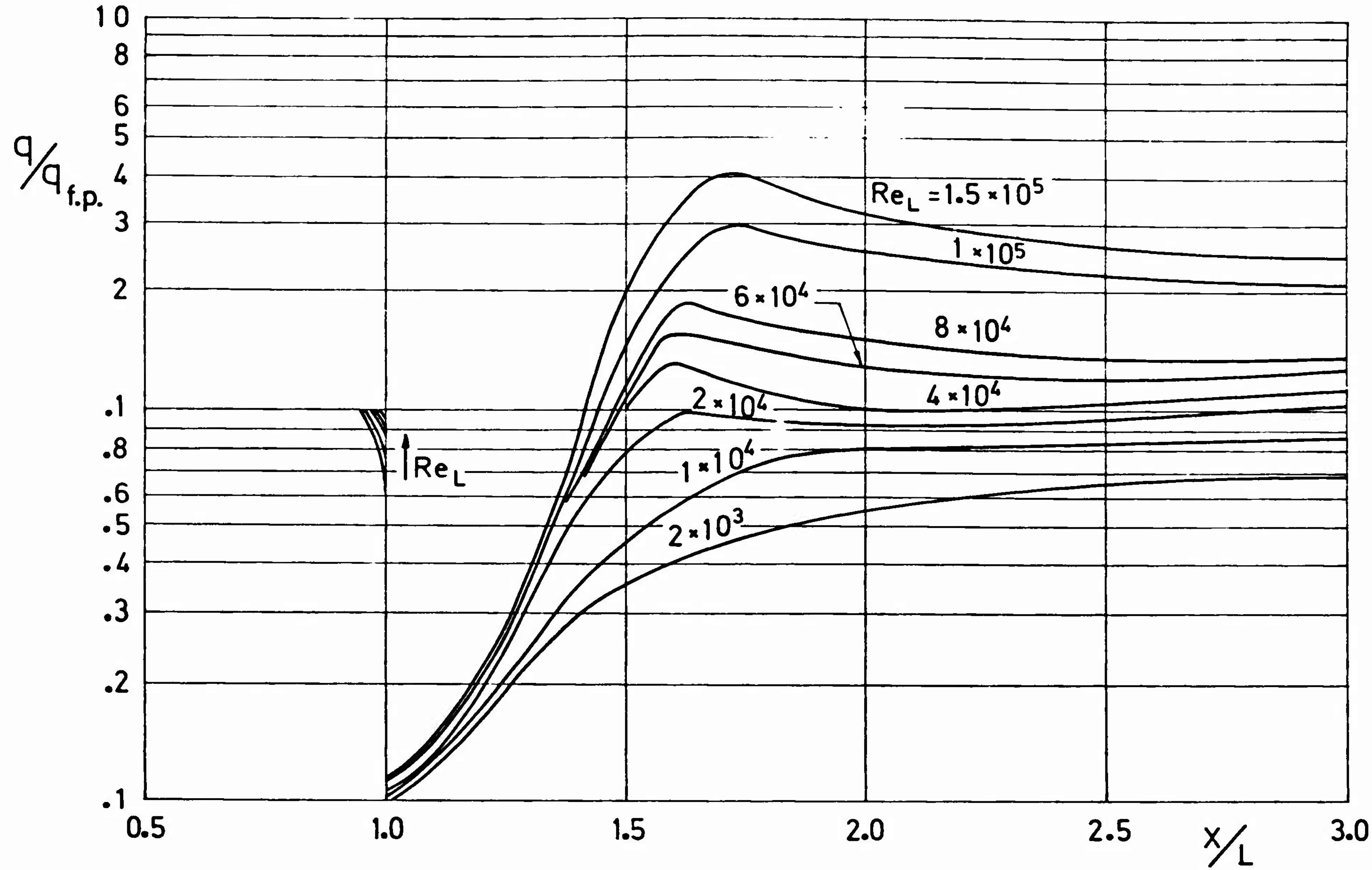

FIG. 14 Calculated local heat transfer rates behind a backward facing step at the flow conditions of the shock tube experiments of Ref. 1.

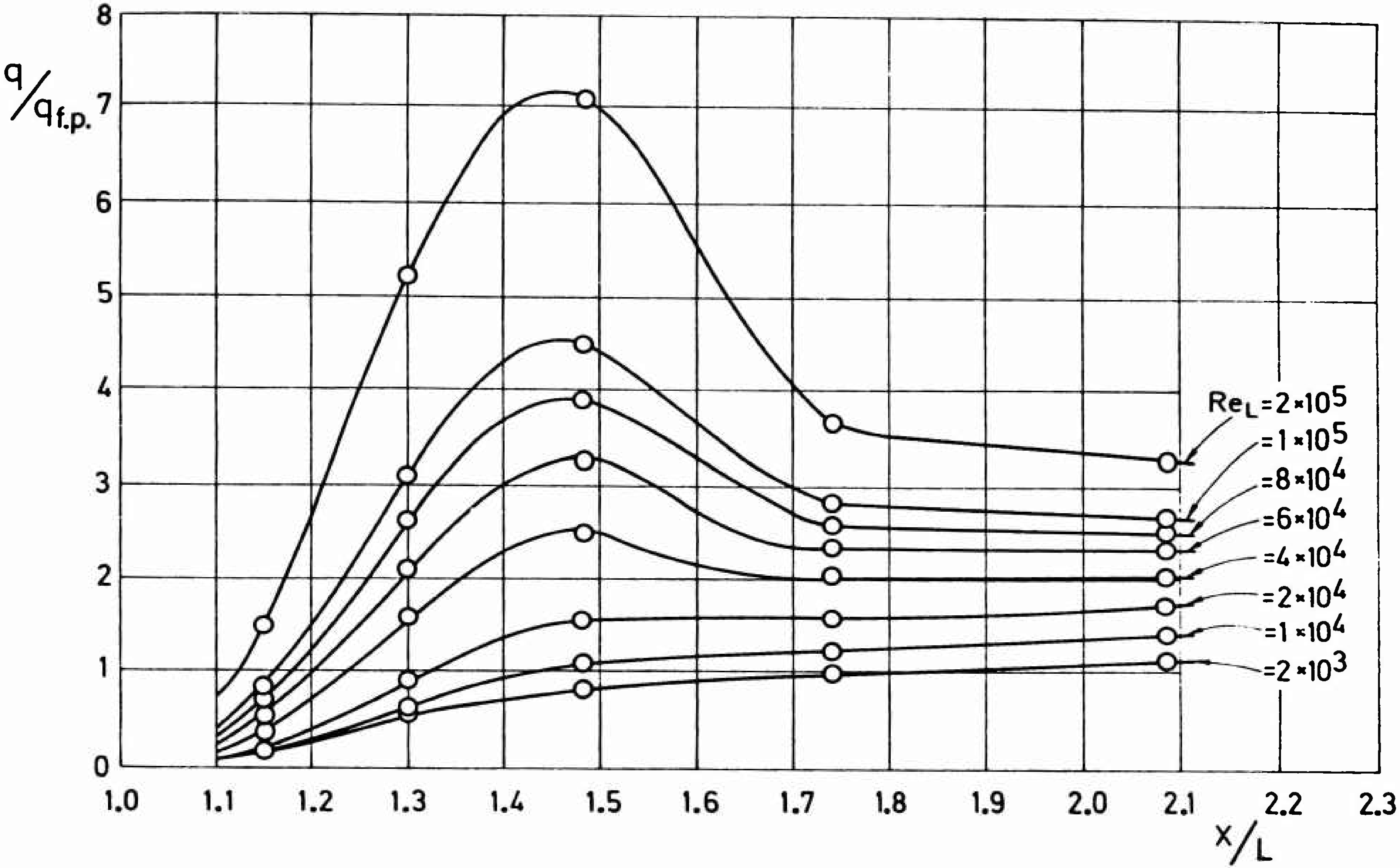

FIG. 15 Measured local heat transfer rates behind a backward facing step (Ref. 1).

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13 ABSTRACT

Heat transfer rate distributions were measured in the separated regions of a two-dimensional backward facing step, an axially symmetric backward facing step, a blunt two-dimensional base, a sharp protruding two-dimensional leading edge and in the leading edge bubble over the surface of a flat nosed two-dimensional model. All measurements were performed in the straight section of the shock tube at shock Mach Numbers between 5.5 to 11, with free stream flow Mach numbers of 1.6 to 2.7, Reynolds numbers (based on the attached flow length or step height) of 3×10^2 to 5×10^5 and stagnation to wall enthalpy ratios of 3 to 50. The results of these measurements are compared with measurements of heat transfer rates in various base type separated flows obtained in various wind tunnels and to a calculation of heat transfer behind a backward facing step based on the integral method. In most of these investigations a high peak in the transfer rate is found to occur in the reattachment zone. Maximum heat transfer rate values of up to 10 times the flat plate heat transfer rate are reported in various investigations. An inverse relation between the value of the peak heat transfer rate and the distance between the separation point to the position of the maximum heating in the reattachment zone is shown exist.

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